



Year: 2014

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DOI: <https://doi.org/10.1016/j.agee.2014.01.020>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-94511>

Journal Article

Originally published at:

Lüscher, Gisela; Jeanneret, Philippe; Schneider, Manuel K; Turnbull, Lindsay A; Arndorfer, Michaela; Balázs, Katalin; Báldi, András; Bailey, Debra; Bernhardt, Karl G; Choisis, Jean-Philippe; Elek, Zoltán;

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DOI: <https://doi.org/10.1016/j.agee.2014.01.020>

Responses of Plants, Earthworms, Spiders and Bees to Geographic Location, Agricultural Management and Surrounding Landscape in European Arable Fields

Gisela Lüscher^{1,2}, Philippe Jeanneret^{1*}, Manuel K. Schneider¹, Lindsay A. Turnbull³, Michaela Arndorfer⁴, Katalin Balázs⁵, András Báldi⁶, Debra Bailey¹, Karl G. Bernhardt⁴, Jean-Philippe Choisis⁷, Zoltán Elek⁹, Thomas Frank⁴, Jürgen K. Friedel⁴, Maximilian Kainz¹⁰, Anikó Kovács-Hostyánszki⁶, Marie-Louise Oschatz⁴, Maurizio G. Paoletti¹¹, Susanne Papaja-Hülsbergen¹⁰, Jean-Pierre Sarthou^{7, 8}, Norman Siebrecht¹⁰, Sebastian Wolfrum¹⁰, Felix Herzog¹

¹ Agroscope, Institute for Sustainability Sciences ISS, Zurich, CH-8046, Switzerland

² Institute of Evolutionary Biology & Environmental Sciences, University of Zurich, Zurich, CH-8057, Switzerland

³ Department of Plant Sciences, University of Oxford, Oxford, OX1 3RB, UK

⁴ University of Natural Resources and Life Sciences Vienna, Vienna, A-1180, Austria

⁵ Institute of Environmental and Landscape Management, MKK, Szent Istvan University, Pater K. u. 1, Gödöllő, H-2100, Hungary

⁶ MTA ÖK Lendület Ecosystem Services Working Group, Alkotmány u. 2-4, Vácraátót, H-2163, Hungary

⁷ Toulouse University, ENSAT, UMR 1248 AGIR, Castanet-Tolosan, F-31326, France

⁸ INRA, UMR 1248 AGIR, Chemin de Borde-Rouge, Castanet-Tolosan, F-31326, France

⁹ MTA-ELTE-MTM Ecology Research Group, Eötvös Loránd University, Biological Institute, Pázmány Péter sétány 1C, Budapest, H-1117, Hungary

¹⁰ Munich Technical University, Freising, D-85350, Germany

¹¹ Department of Biology, Padova University, via U. Bassi 58/b, Padova, I-35121, Italy

* Corresponding author: philippe.jeanneret@agroscope.admin.ch, Tel +41 58 468 72 28.

Abstract

Farmland species provide key ecological services that support agricultural production, but are under threat from agricultural intensification and mechanization. In order to design effective measures to mitigate agricultural impact, simultaneous investigations of different taxonomic groups across several regions are required. Therefore, four contrasting taxonomic groups were investigated: plants, earthworms, spiders and bees (wild bees and bumblebees), which represent different trophic levels and provide different ecological services. To better

understand underlying patterns, three community measurements for each taxonomic group were considered: abundance, species richness and species composition. In four European regions, ten potential environmental drivers of the four taxonomic groups were tested and assigned to three groups of drivers: geographic location (farm, region), agricultural management (crop type, mineral nitrogen input, organic nitrogen input, mechanical field operations and pesticide applications) and surrounding landscape in a 250 m buffer zone (diversity of habitats in the surroundings, proportion of arable fields and proportion of non-productive, non-woody habitats). First, the variation in abundance, species richness and species composition from 167 arable sites was partitioned to compare the relative contribution of the three groups of drivers (geographic location, agricultural management and surrounding landscape). Second, generalized linear mixed-effects models were applied to estimate the effect of the individual explanatory variables on abundance and species richness. Our analysis showed a dominant effect of geographic location in all four taxonomic groups and a strong influence of agricultural management on plants, spiders and bees. The effect of the surrounding landscape was of minor importance and inconsistent in our data. We conclude that in European arable fields, the avoidance of mineral nitrogen and pesticides is beneficial for biodiversity, and that species protection measures should take into account regional characteristics and the community structure of the investigated taxonomic groups.

Keywords

Abundance, Species richness, Species composition, Partitioning of variation, BioBio

1. Introduction

Although the production of agricultural goods depends, in part, on ecological services provided by farmland species, human activities often impair biodiversity (Hector and Bagchi, 2007; Sachs et al., 2009). Intensive agricultural management may deplete beneficial species

that contribute to, for example, soil fertility, decomposition, biological control or pollination (Costanza et al., 1997). Such species are particularly threatened in arable fields, which face regular disturbances due to intensive management for optimized resource use and crop protection (Matson et al., 1997; Robinson and Sutherland, 2002).

Agri-environment schemes are implemented to mitigate the pressure on biodiversity and to promote farmland species. While they have frequently been shown to benefit farmland species, the magnitude of the effects has varied among studies (Batáry et al., 2010; Gibson et al., 2007). These ambiguous results have been attributed to differences in taxonomic groups, study regions and scales of investigation (Bengtsson et al., 2005). In addition, several studies have concluded that more detailed insights into the drivers of farmland species could be achieved if both landscape characteristics and management practices were considered (Batáry et al., 2011; Chaplin-Kramer and Kremen, 2012; Concepción et al., 2012a; Schweiger et al., 2005; Tschardt et al., 2005).

Many studies of farmland species have been limited to only one or a few popular taxonomic groups. However, the effects of agricultural management and of landscape characteristics on a particular taxonomic group are likely to depend on its specific resource needs, such as food or habitat requirements (Aviron et al., 2009; Báldi et al., 2013; Kleijn et al., 2006; Schuldt and Assmann, 2010). In order to promote agricultural practices with targeted benefits for biodiversity, it is therefore important to evaluate their impacts on multiple taxonomic groups. Further, it may also be important to evaluate multiple community measurements such as abundance, species richness and species composition, as these may have different specific effects on ecological services (Isbell et al., 2011) and different sensitivities to the agricultural environmental drivers (Jeanneret et al., 2003; Worthen, 1996).

Here, we investigated plant, earthworm, spider and bee (wild bee and bumblebee) communities in 167 arable fields across four European regions. The four taxonomic groups were chosen because they have different habitat and food requirements, provide a range of ecological services and occupy different trophic levels. Plants, as primary producers and sessile organisms, depend on light, water and nutrients available on site. Plant abundance and species richness in arable fields have been found to decrease due to management intensity (mineral nitrogen input, pesticide applications) in numerous studies, e.g. Hyvönen and Salonen (2002) and Rassam et al. (2011). Further, plant diversity, mainly in field edges, is enriched by a higher amount of semi-natural habitats in the surrounding landscape (Concepción et al., 2012b; Kovács-Hostyánszki et al., 2011). Earthworms, as detritivores and soil organisms, contribute to soil fertility. They are positively affected by the application of solid manure, mulches and reduced tillage (Chan, 2001). Spiders are a widely distributed and highly abundant group of predators for which several studies have emphasized the significance of (perennial) vegetation structure (e.g. Gibson et al., 1992 or Schmidt and Tscharncke, 2005). Wild bees and bumblebees act as pollinators and are highly mobile. They depend on a continuous pollen and nectar supply in the wider landscape and on appropriate nesting sites (e.g. Kremen et al., 2007).

We tested how plant, earthworm, spider and bee communities in the same arable fields responded to explanatory variables representing geographic location, agricultural management and surrounding landscape. For all communities, abundance, species richness and species composition were considered to gain more information on community patterns than one measurement alone could provide. The four taxonomic groups were expected to differ in their responses, and that these differences were reflected in existing or missing correlations among the taxonomic groups. However, because arable fields are predominantly shaped by agricultural practices for the purpose of crop production, we hypothesized that management

variables have a significant effect on the four taxonomic groups, independent of geographic location and surrounding landscape.

2. Materials and Methods

2.1. Study Sites

Data collection was part of the EU-FP7 project BioBio, which investigated and proposed a set of biodiversity indicators applicable for European farmland monitoring (Herzog et al., 2012). This study investigated 167 arable fields from four European regions: Marchfeld (Austria), Southern Bavaria (Germany), Gascony (France) and Homokhátság (Hungary).

Each region was an environmentally homogeneous area, representing either typical arable cropping or a combination of arable cropping and grassland-based livestock farming (Table 1). In each region of approximately 1000 km², between 14 and 16 study farms, half of them organic and half non-organic, were randomly selected. The whole area of these farms was mapped by classifying different habitat types according to primary life forms, environment and management (Bunce et al., 2008). One of four crop categories was assigned to each arable field: winter cereals, spring cereals, forage crops (e.g. lucerne, grass-clover) and others (e.g. oilseed rape). For each available crop category per farm, one field was randomly selected for species sampling.

Table 1: Geographic coordinates, environmental and agricultural characteristics of the study regions.

Region	Marchfeld	Southern Bavaria	Gascony	Homokhátság
Country	Austria	Germany	France	Hungary
Latitude (°)	48.3	48.4	43.4	46.7
Longitude (°)	16.7	11.3	0.8	19.6
Altitude (m asl)	140-180	350-500	197-373	93-168
Climate	Pannonian	Continental	Sub-Mediterr.	Pannonian
Rainfall (mm)	560	800	680	550
Mean annual temp. (°C)	9.5	8.5	13	10.4
Soil	Deep fertile chernozem	Silt and silt loam	Clay-limestone	Sandy
Production type	Arable crops	Mixed	Arable crops	Mixed
# Arable fields (in # farms)	56 (16)	49 (16)	39 (15)	23 (14)

2.2. Species Sampling

In each randomly selected arable field, species of the four taxonomic groups were sampled from spring to early autumn in 2010 according to standardized protocols (Dennis et al., 2012). Sample locations were chosen such that edge effects were avoided. Plant surveys were conducted once, in a plot of 10 m × 10 m. All species were recorded and their respective cover estimated. Cultivated crop species were excluded from the analysis except the forage crops. Earthworms were collected at three random locations per field, at one time. A solution of allyl isothiocyanate (0.1 g/l) was poured into a metal frame of 30 cm × 30 cm in order to encourage earthworms to move to the surface. Subsequently, earthworms were collected by hand from a 20 cm deep earth core. Identification and counting of earthworms species was conducted in the lab. Non-clitellates (juveniles and subadults) were excluded from the analysis. Spiders were sucked from the surface at three dates during the season from within five randomly located circular areas of 35.7 cm diameter per field using a modified leaf blower. The samples were frozen and adults were identified in the lab. Wild bee and bumblebee species were sampled during good weather conditions, i.e. during periods of sunshine when it was not too windy and the temperature was higher than 15 °C. Bees were

sampled on three dates with a handheld net along a 100 m × 2 m transect traversing the plant survey plot for 15 min, except in the Marchfeld region, where bees were sampled only twice due to bad weather. Honeybees (*Apis mellifera*) were excluded from the analysis.

2.3. Response Variables

Three community measurements were calculated as response variables: abundance, species richness and species composition. Abundance was expressed as the percentage cover for plants and the total number of individuals per field for earthworms, spiders and bees. Species richness was calculated as the total number of species in a field. Species composition was quantified as the species list for each taxonomic group, accounting for abundance per field.

2.4. Explanatory Variables

Potential environmental drivers were divided into three groups of variables for (1) geographic location, (2) agricultural management and (3) surrounding landscape.

Geographic location: Two variables, farm (fields belonged to 61 farms) nested within region (four groups), were assigned to each investigated field as descriptors of general geographic conditions. The variable farm accounted for general features of the farm (e.g. location, overall farming intensity or the crop rotation system). The variable region incorporated characteristics such as climatic conditions, soil properties and large-scale landscape features (e.g. exclusively arable cropping or mixed farming, occurrence of forest or water bodies) as well as historic processes of landscape changes.

Agricultural management: For all investigated fields, management practices in 2010 were recorded in structured interviews with farmers. Since a large number of agricultural management variables were partially correlated, we pre-selected the five that were only weakly correlated using correlation coefficients and variance inflation factors, according to Borcard et al. (2011). The final group of agricultural management variables consisted of: crop

type, amount of mineral nitrogen (N) fertilizer applied, amount of organic nitrogen (N) fertilizer applied, number of mechanical field operations and number of synthetic and natural pesticide applications. For the analysis, we regrouped the original division of four crop types into six crop types according to sowing time and management practices (winter cereals, spring cereals, Fabaceae, forage plants, maize/sunflower and miscellaneous crops such as oilseed rape, potato or sugar beet). Winter cereals were the most abundant crop type, followed by forage plants and maize/sunflower (Table 2). In general, fields with Fabaceae and forage plants were less intensively managed regarding N input and pesticide applications than fields sown with miscellaneous crops and maize/sunflower. In order to detect the specific drivers (e.g. mineral N input or pesticide applications) of community structures, organic and non-organic fields were not separated in the analysis. The N input and the mechanical field operations were remarkably high in Southern Bavaria (Table 2). Pesticides were applied on 58 of the 167 fields, 34 fields were treated more than once. Pesticides were mainly herbicides, fungicides and rarely insecticides, retardants or molluscicides.

Surrounding landscape: Based on aerial photographs, the landscape composition was recorded in a buffer zone around each investigated field. The radius of the buffer zone was set at 250 m as a compromise for the four contrasting taxonomic groups (Gaba et al., 2010; Schmidt et al., 2008; Zurbuchen et al., 2010). Initially, the buffer zone was subdivided into nine habitat categories, and the estimates of percentage of habitat cover were used to calculate a Shannon diversity index H (based on the natural logarithms) of the surrounding habitats for each field. Then, the percentage cover of four aggregated habitat groups was calculated: (a) arable fields, (b) grasslands, (c) woody habitats (forest, scrub and woody crops) and (d) non-productive, non-woody habitats (urban area, sparsely vegetated ground, aquatic habitats, emergent hydrophytes or helophytes). Similar to agricultural management variables, the number of surrounding landscape variables was reduced to three: diversity of habitats in the

surroundings, proportion of arable fields and proportion of non-productive, non-woody habitats (Table 2).

Table 2: Characteristics of the investigated arable fields: mean \pm standard error of numeric variables and levels of the categorical variable crop type in each study region (in order of frequency).

Region				Marchfeld	Southern Bavaria	Gascony	Homokhátság
Agricultural management	Mineral (kg/ha)	N	input	40 \pm 7	52 \pm 9	34 \pm 8	2 \pm 2
	Organic (kg/ha)	N	input	7 \pm 3	56 \pm 6	16 \pm 5	53 \pm 10
	Field operations			6 \pm 0.3	12 \pm 1	5 \pm 0.4	3 \pm 0.2
	Pesticide applications			1 \pm 0.2	0.8 \pm 0.2	0.9 \pm 0.2	0
	Crop types			WiC, For, Fab, M/S, Mis, SpC	WiC, For, M/S, Fab, Mis	WiC, S, Fab, For, SpC	For, WiC, M/S
Surrounding landscape	H ^a of surrounding habitats			0.2 \pm 0.04	0.9 \pm 0.04	0.7 \pm 0.05	0.8 \pm 0.05
	Arable fields (%)			90.2 \pm 2.2	63.7 \pm 2.3	74.9 \pm 2.6	43.5 \pm 3.9
	Non-productive, non-woody habitats (%)			3.9 \pm 1.5	6 \pm 0.8	2.4 \pm 0.8	5.7 \pm 2.4

Abbreviations for the crop types: WiC, winter cereals; SpC, spring cereals; For, forage crops; Fab, Fabaceae; M/S, maize/sunflower; Mis, miscellaneous crops.

^a H = Shannon diversity index

2.5. Data Analysis

The relative roles of the three groups of explanatory variables were calculated: geographic location, agricultural management and surrounding landscape on the three response variables per taxonomic group.

Partitioning of variation was used to quantify the variation in abundance, species richness and species composition due to the three groups of explanatory variables (Borcard et al., 2011). The three groups were not fully independent of each other; therefore, some variation was explained jointly by two or by all three groups. The percentages of variation due to a single group of explanatory variables or a combination of groups were reflected in the adjusted R^2 , which were calculated by partial redundancy analysis (RDA). Significance of percentages allocated to single groups was assessed based on 999 permutations (Legendre and Legendre,

2012). Because partitioning of variation relies on linear regressions, the univariate response variables, abundance and species richness, were log-transformed after adding a constant $c = 0.5$ ($\frac{1}{2}$ of the smallest non-zero value). Species composition data, as multivariate response variables, were Hellinger transformed (Legendre and Gallagher, 2001).

Generalized linear mixed-effects models were used to analyse effects of the individual explanatory variables on abundance and species richness. Since the response variables were over-dispersed with respect to a Poisson model, we assumed that they followed a negative binomial distribution. Bee data contained more than 60% zeros. Therefore, we applied models that accounted for zero-inflation. Agricultural management and surrounding landscape variables were treated as fixed effects, and interactions among fixed effects were included when significant. Region was included as a random intercept in all models. If, as an additional random intercept, farm improved the fit of the model significantly, it was included, also. The influence of individual crop types was tested against the most abundant crop type, the winter cereals. Models were reduced based on the AIC (Akaike information criterion) corrected for small samples (Burnham and Anderson, 2002). The significance of the reduced models was assessed with sequential likelihood-ratio tests.

Correlations in abundance, species richness and species composition among the four taxonomic groups, were calculated separately for all four regions based on untransformed species data. For abundance and species richness, Spearman's rank correlation coefficients were calculated in order to account for the non-normal distribution of the data. Procrustes rotation was used to test for correlations among the species compositions of the four taxonomic groups (Legendre and Legendre, 2012).

All analyses were performed in R 2.15.3 (R Development Core Team, 2012) using packages *vegan* 2.0-6, *vennerable*, *plotrix*, *glmmADMB* 0.7.3, *AICcmodavg* 1.27 and *lmtree*.

3. Results

In the entire set of 167 arable fields, 2,565 adult earthworm individuals, 1,967 adult spider individuals and 343 bee individuals were found. We identified 292 plant species, 19 earthworm species, 158 spider species and 72 wild bee and bumblebee species. The complete species lists and the number of fields in which they occurred are provided in Appendices S2, S3, S4 and S5 in Supplementary Material. In the Gascony region, the highest number of species was recorded for all four taxonomic groups (Fig. 1). For plants, 5% of all species occurred in all four regions and covered 30% of the area investigated (167 x 100 m²). Five common species in all four regions with a high overall abundance were *Chenopodium album*, *Cirsium arvense*, *Convolvulus arvensis*, *Lolium perenne* and *Medicago sativa*. For earthworms, the most common species were *Allolobophora caliginosa* and *A. rosea*, which accounted for 55% of all earthworm individuals. For spiders, 4% of all species were recorded in all regions, and these made up 34% of the total spider abundance. The spider species *Erigone dentipalpis*, *Meioneta rurestris* and *Pachygnatha degeeri* were highly abundant and are among others listed by Schmidt and Tschamntke (2005) as so called agrobionts, i.e. species that “invariably dominate spider communities in crop fields over large parts of Europe.” One bumblebee species, *Bombus terrestris*, was common in all regions, accounting for 13% of all bee individuals.

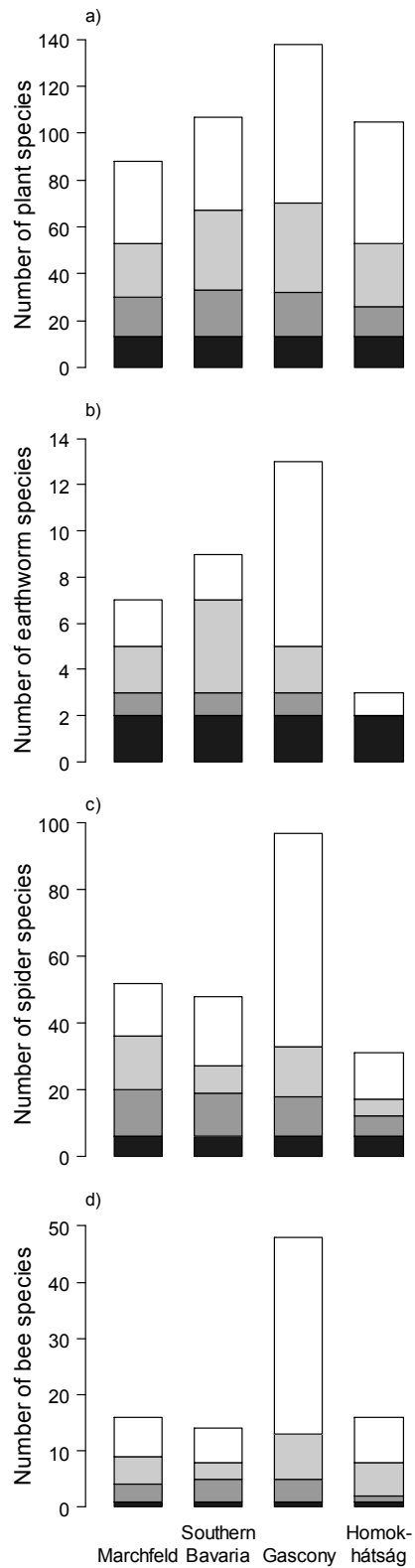


Fig. 1: Total number of (a) plant, (b) earthworm, (c) spider and (d) bee species in each region. Grey shading indicates the number of species occurring: in all four regions (black), in three regions (dark grey), in two regions (light grey), exclusively in the corresponding region (white).

3.1. Plants

Variation in plant abundance of non-crop species was primarily explained by agricultural management (22%) and geographic location (18%), but not by surrounding landscape (Fig. 2). Variation in plant species richness was mainly explained by combinations of geographic location, agricultural management and surrounding landscape. None of the groups of explanatory variables explained a significant percentage of the variation independently of other variables. The variation in plant species composition was equally well explained by geographic location (10%) and agricultural management (10%), but not by surrounding landscape.

The generalized linear mixed-effects model revealed a negative effect of mineral N input and a positive effect of organic N input on plant abundance (Table 3). The interaction of organic N input and the proportion of arable fields in the surroundings was negative. This indicated that the positive effect of the combination of the both variables was weaker than the sum of the two variables. Crop type was also important: plant abundance in winter cereal fields was significantly lower than in forage fields and was significantly higher than in maize/sunflower fields. Mineral N input and pesticide applications had a negative effect on plant species richness (Table 4). Further, the interactions of mineral N input and pesticide applications and of mineral N input and mechanical fields operations were significantly positive. Thus, the detrimental effect of the two involved variables in combination was weaker than the sum of them. Plant species richness was significantly higher in winter cereal fields than in maize/sunflower fields, and the diversity of habitats in the surroundings had a positive effect.

3.2. Earthworms

Variation in earthworm abundance, species richness and species composition was predominantly explained by geographic location at percentages of 55%, 47% and 21%,

respectively (Fig. 2). Neither agricultural management nor surrounding landscape explained a significant percentage of variation in earthworm communities independently.

Also in the mixed models, none of the agricultural management and surrounding landscape variables had a significant effect on earthworm abundance and species richness (Table 3 and 4).

3.3. Spiders

Variation in spider abundance, species richness and species composition was similarly significantly explained by geographic location (11%, 12% and 10%, respectively) and agricultural management (9%, 6% and 6%, respectively), but not by surrounding landscape (Fig. 2).

The mixed model indicated a positive effect of organic N input on spider abundance and species richness (Table 3 and 4). Furthermore, spider abundance and species richness were significantly higher in forage fields than in winter cereal fields, and maize/sunflower fields harboured significantly fewer spider species than winter cereal fields.

3.4. Bees

Variation in bee abundance and species richness was largely explained by geographic location (22% and 15%, respectively) but not by agricultural management or surrounding landscape (Fig. 2). Bee species composition was highly variable and none of the groups of explanatory variables tested had a significant effect.

The mixed models showed a negative effect of pesticide applications on bee abundance and species richness (Table 3 and 4). Mineral N input affected bee species richness negatively. Both, abundance and species richness, were higher in forage fields than in winter cereal fields. Furthermore, habitat diversity as well as the proportion of arable fields and the proportion of non-productive, non-woody habitats in the surroundings decreased bee abundance and species

richness. The interaction of habitat diversity and the proportion of non-productive, non-woody habitats was positive for bee abundance and species richness and the interaction of the proportion of arable fields and the proportion of non-productive, non-woody habitats also for species richness. This indicated that the detrimental effect of the two involved variables in combination was weaker than the sum of them.

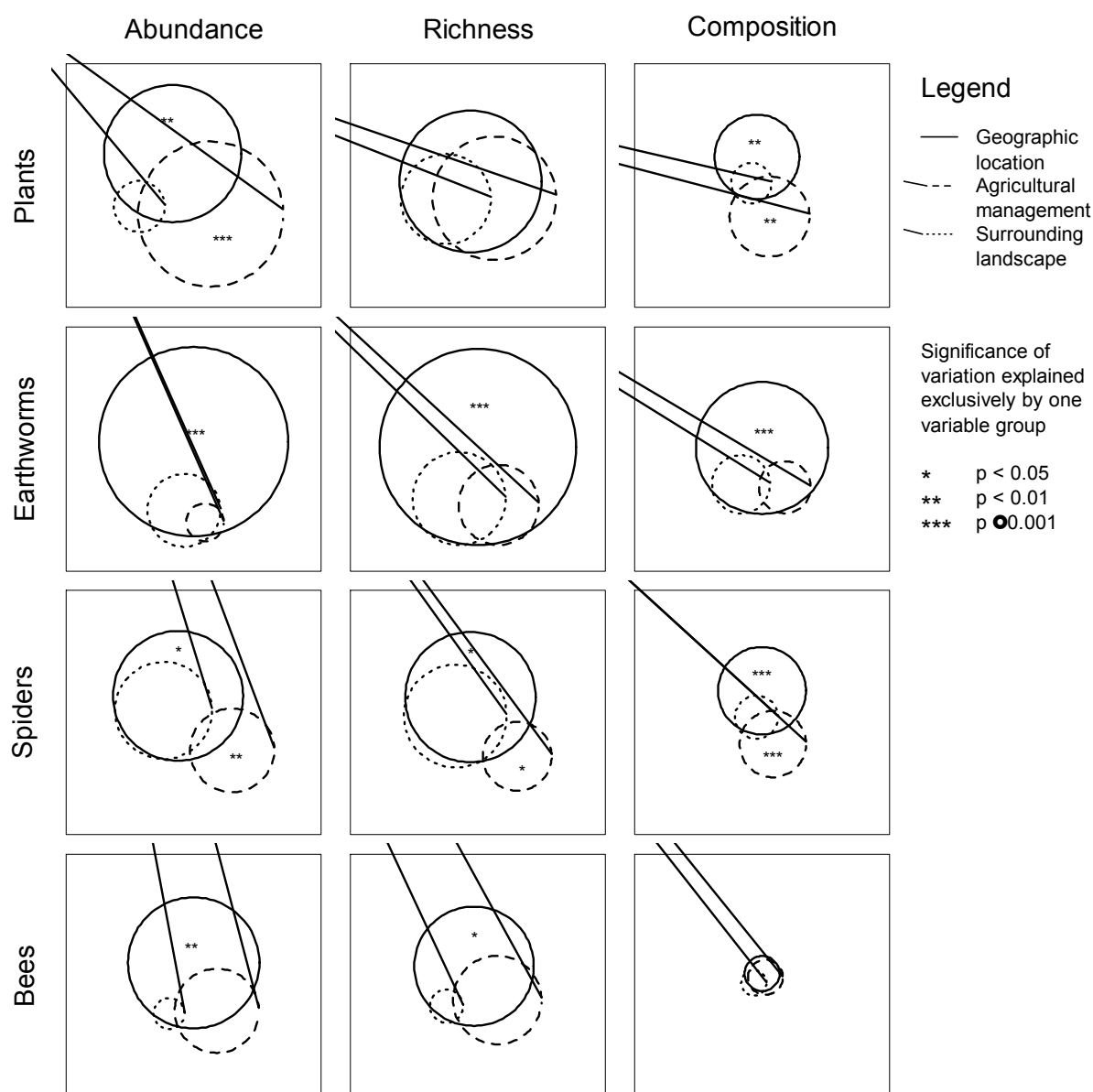


Fig. 2: Partition of variation in abundance, species richness and species composition of plants, earthworms, spiders and bees explained by geographic location, agricultural management and surrounding landscape derived from partial redundancy analysis. The area of the circles is proportional to the percentage of variation explained by the respective group of explanatory variables. Each box accounts for the total variation (100 %), i.e. the area outside of the circles represents the amount of unexplained variation.